Ice Particle Transport Analysis With Phase Change for the E^3 Turbofan Engine Using LEWICE3D Version 3.2

Colin Bidwell

NASA Glenn Research Center

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Outline

- Analytical Method
  - ADPAC
  - LEWICE3D Version 3.2
- Analysis
- Conclusions

Schematic of High Fidelity Engine Icing Analysis

GRID GENERATOR

Develop 3D structured or unstructured grids: GRIDGEN

↓

FLOW SOLVER

3D steady, mixing plane based flow solver: Glenn HT, ADPAC

↓

ICE ACCRETION CODE

3D Ice accretion tool with “block-to-block” particle transport method: LEWICE3D V3.2

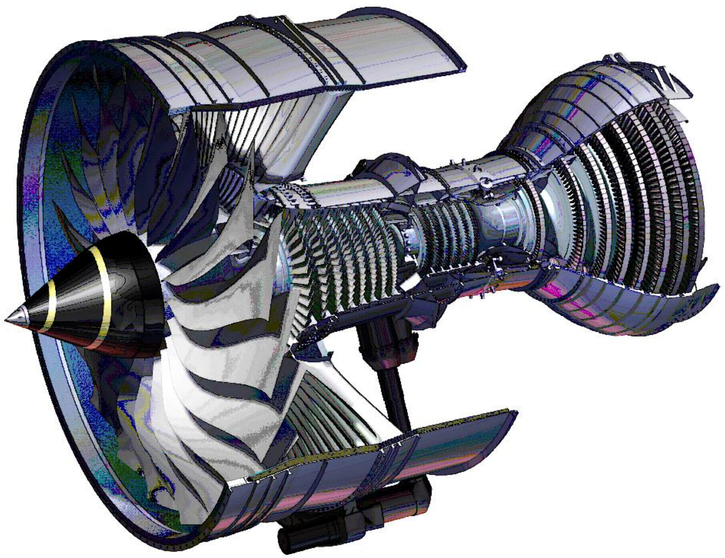
ADPAC Flow Solver

- Three-dimensional, finite volume, Reynolds Averaged, Navier-Stokes flow solver.
- Computes flows for complex propulsion system configurations using multi-block, body fitted grids.
- Employs a mixing plane procedure to pass boundary condition data between grid blocks for steady flows.
- Employs a Baldwin-Lomax based turbulence model.
- Supports parallel computing on multiple platforms.

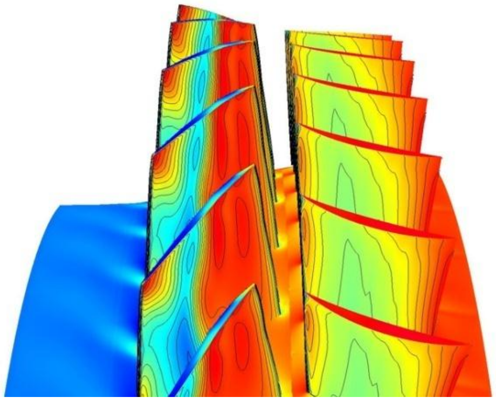
LEWICE3D Version 3.2

- Version 3.2 Features (Release Date May 2012)
  - A grid block transformation scheme which allows the input of grids in arbitrary reference frames, the use of mirror planes, and grids with relative velocities has been developed.
  - A new packet based collection efficiency algorithm was developed which calculates particle trajectories from inflow block boundaries to outflow block boundaries. This method is used for calculating and passing collection efficiency and particle property data between blade rows for turbomachinery calculations.
  - A simple ice crystal and sand particle bouncing scheme has been included.
  - Added an SLD splashing model based on that developed by William Wright for the LEWICE 3.2.2 software.
  - The NASA Glenn Ice Crystal Phase Change Model was incorporated which tracks temperature and phase of water based particles through the flow-field
  - Dynamic memory allocation and OpenMP and MPI parallelization has been incorporated to optimize memory and speed on modern computers.
- Approximations
  - Single time step
  - Ice shapes calculated along 3D strips
  - Steady or time averaged flow solutions required
  - Grid based application requires user supplied 3D flow solutions on structured, or unstructured grids
  - Messinger quasi-steady control volume icing model
  - Heat transfer calculated using integral boundary layer algorithm with roughness effects
  - Surface water loading generated from trajectories calculated from upstream to surface

A Typical 3D, Steady Turbomachinery Flow Analysis Represents Blade Rows with a Single Blade using Average Inflow/Outflow Boundary Conditions (Mixing Plane)



Typical turbofan engine has many stages in the compressor and turbine section

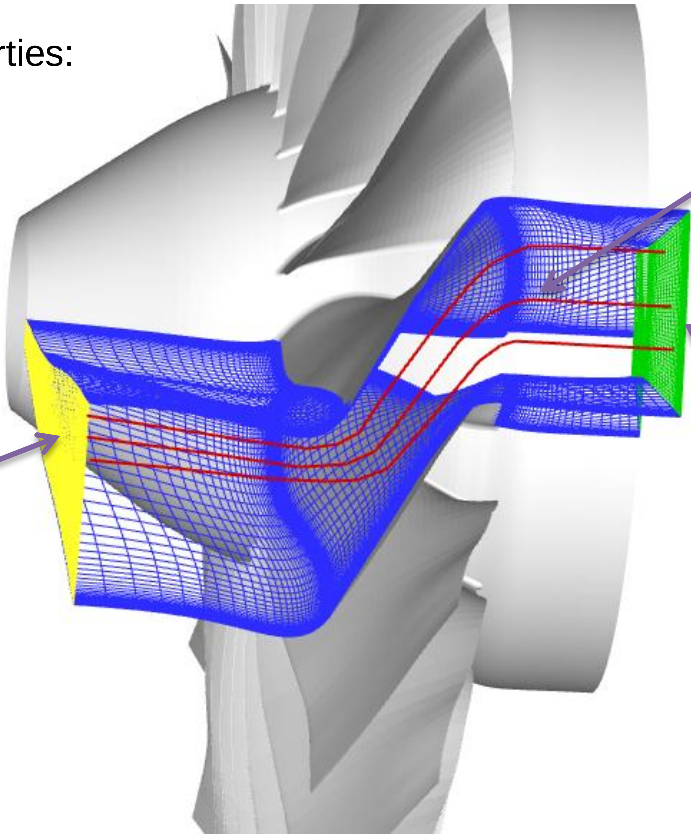


Stage flow modeled using single blade and average inflow/outflow boundary conditions (mixing plane)

Schematic of Particle Trajectories Traversing a Single Blade Row for the "Block-to-Block" Particle Transport Method

$H_2$0 Particle Transport Properties:

- Position
- Velocity
- Diameter
- Temperature
- Melt Fraction



Trajectories

Out-flow boundary for grid block

In-flow boundary for grid block

LEWICE3D Rebound Model

A simple rebound model was incorporated into the LEWICE3D V3.2 to calculate impacting ice particles (IREBOUNDMODEL=1,2 Namelist TRAJ). The model assumes spherical particles with no rotation and no breakup or deformation. The LEWICE3D V3.2 model represents the resulting ice particle velocity using a model based on coefficient of restitution and a coefficient of dynamic friction. The velocity of the rebounding particle from the model is:

$$V_{n_2} = -K V_{n_1}$$

$$V_{t_2} = V_{t_1} - f(1+K) V_{n_1}$$

where:

V_{n_1} = Normal velocity of particle impacting surface

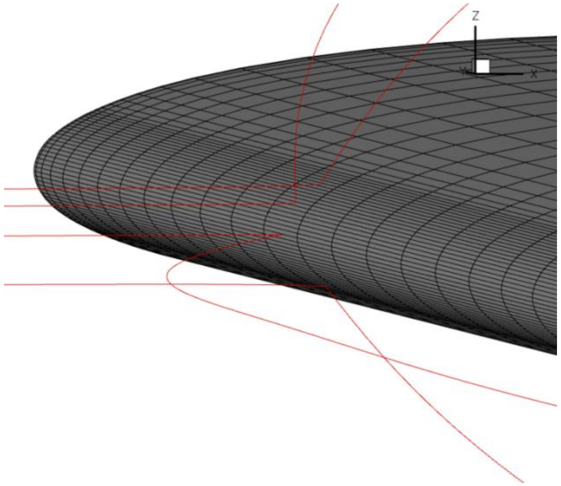
V_{n_2} = Normal velocity of particle reflected from surface

V_{t_1} = Tangential velocity of particle impacting surface

V_{t_2} = Tangential velocity of particle reflected from surface

K = Coefficient of Restitution (0-1)

f = Coefficient of Dynamic Friction (0-1)

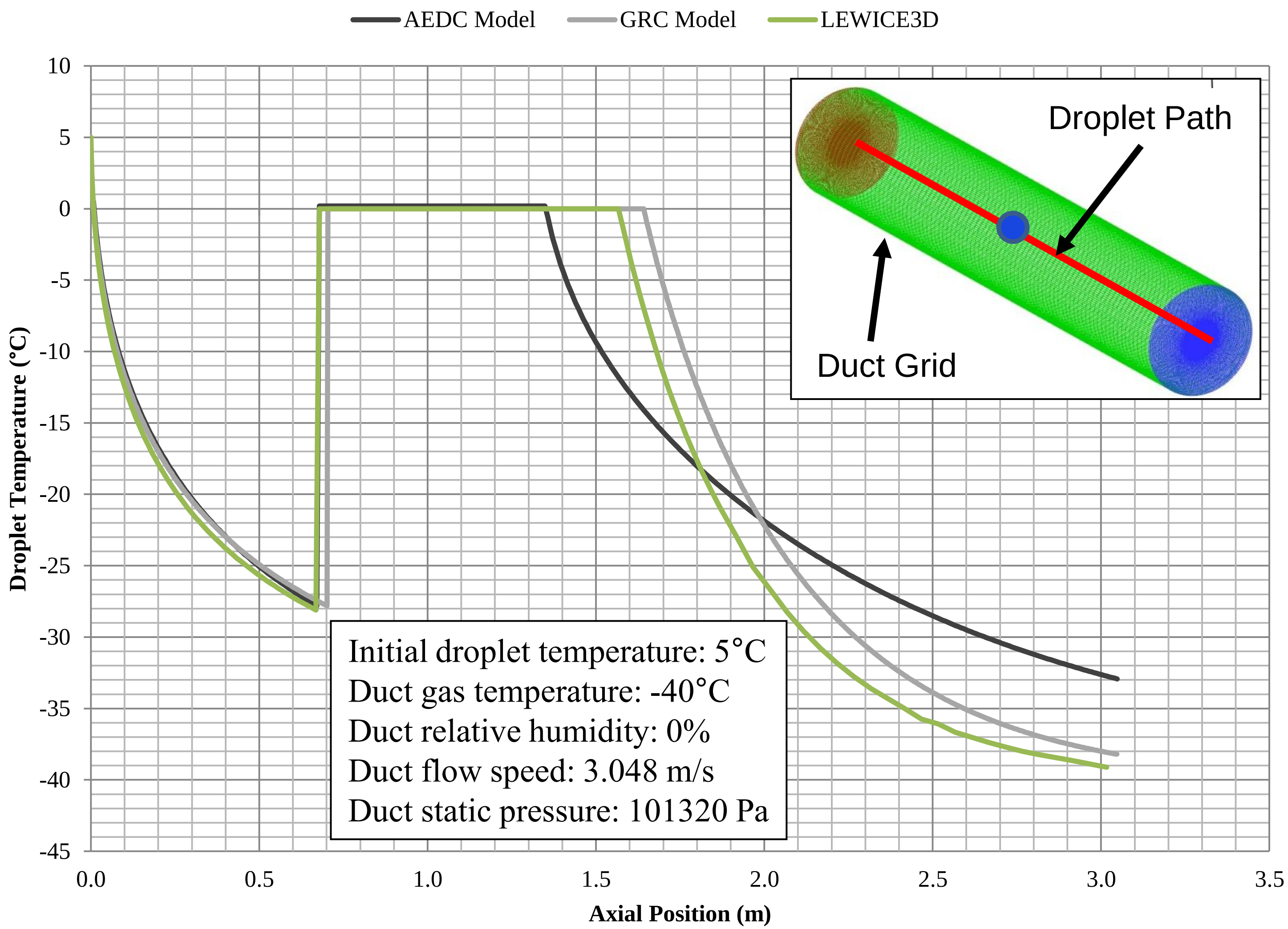


LEWICE3D Glenn Phase Change Model

- Models the freezing or melting of H_2O based particles with mass loss (i.e. sublimation, evaporation).
- Incorporated the model into the variable time stepping scheme used to calculate particle trajectories in LEWICE3D.
- Glenn Phase Change Model Assumptions:
  - All gases are treated as ideal.
  - All droplets are treated as perfect spheres and are assumed to be homogeneous in temperature.
  - No coupling of the H_2O particle regime and the surrounding flowfield (i.e. gas temperature, velocity and pressure are assumed to not change as a result of mass or heat transfer between particles and gas).
  - Mass transfer is always at equilibrium. The particle surface is considered to always be at saturation pressure at the particle temperature.
  - The gas is extremely clean. The only condensation possible is on the droplets, so that the gas can become supersaturated.
  - Thermal and kinetic energy do not convert from one to the other.
  - Unless a particle is fully solidified, its surface is liquid.
  - The thermodynamic properties of dry gas and humid gas are equivalent.

Droplet Temperature For Straight Duct Freezing Test Case

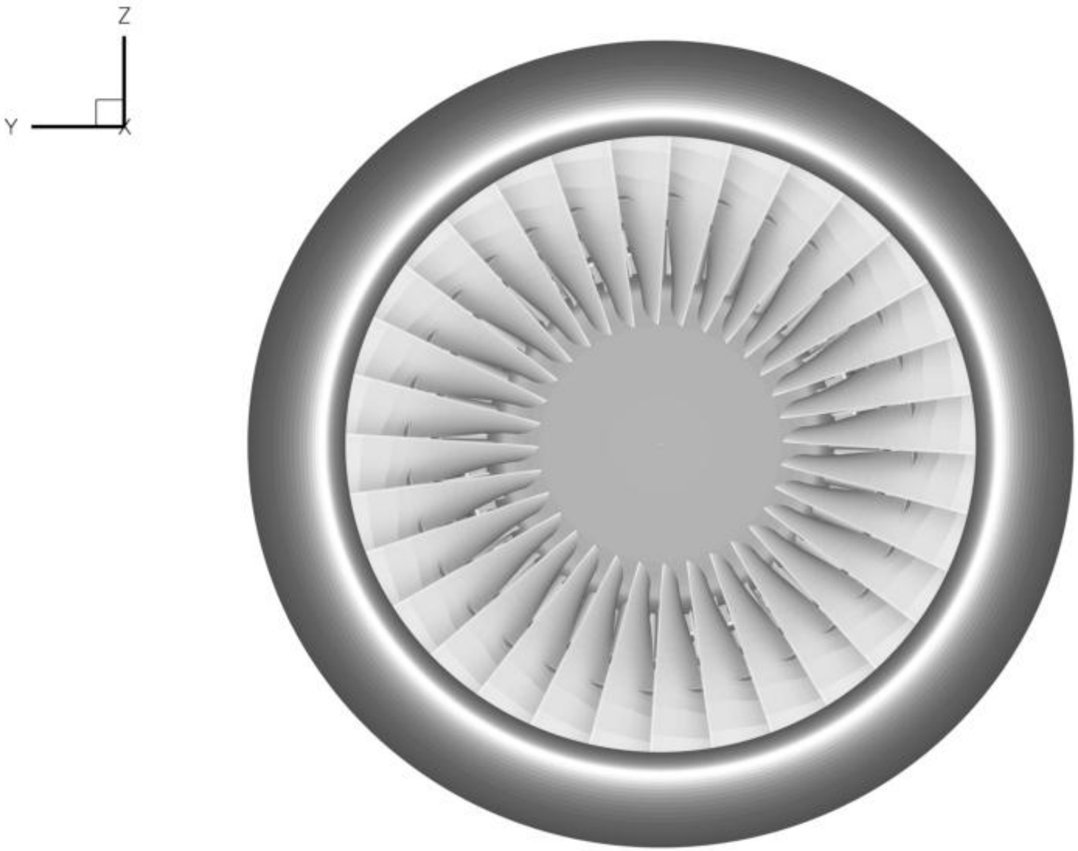
Droplet Size; 50 µm



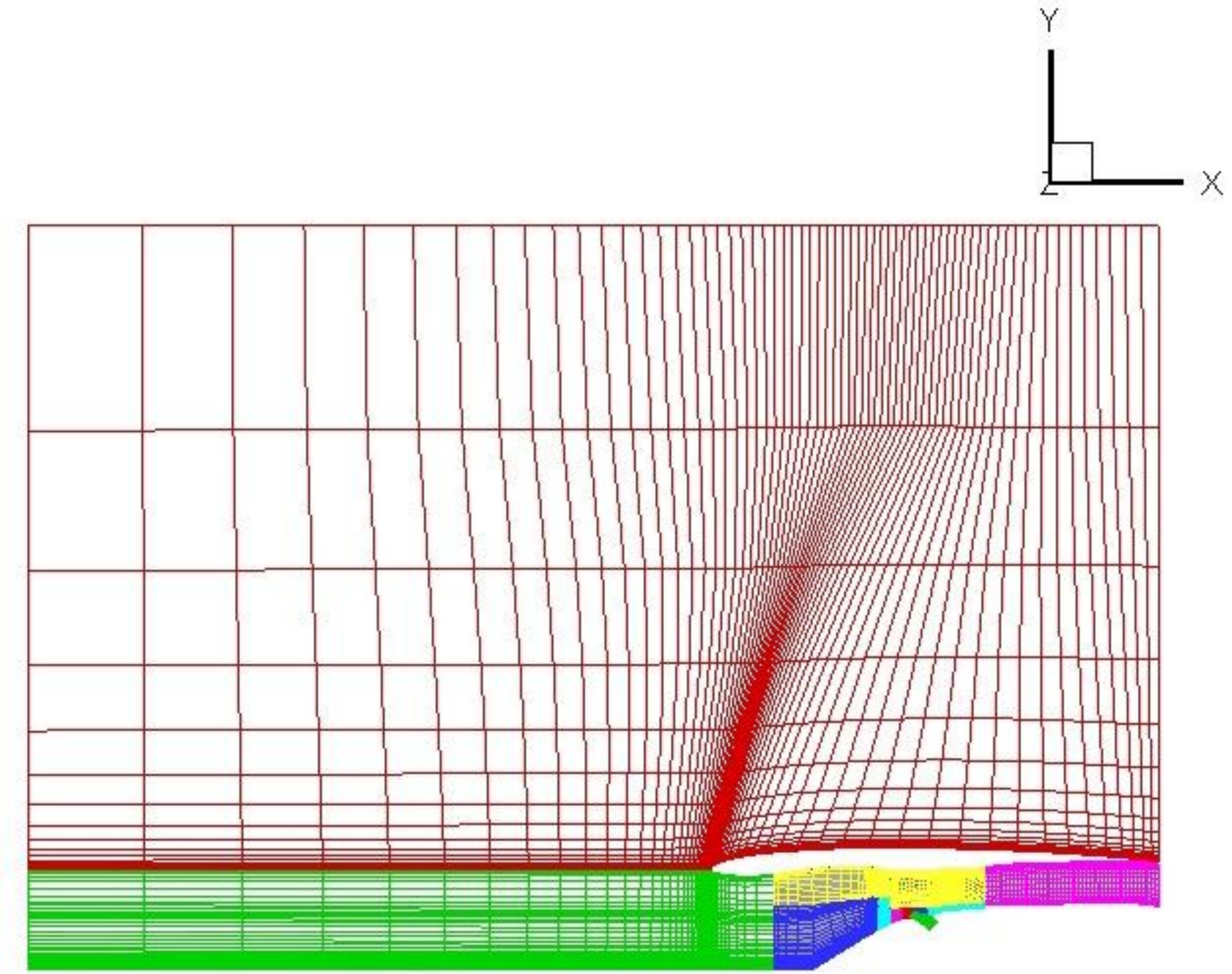
Analysis

- ADPAC flow was used for the particle trajectory and icing analysis.
  - The computational grid contained 12 structured abutted grid block with 327,583 nodes.
  - The steady, viscous flow solution was generated for a Mach .8 cruise condition at 11,887 meters assuming a standard warm day atmosphere.
- Particle trajectory calculations were made for ice particle sizes of 5, 20 and 100 μm assuming a free stream particle concentration of 0.3 g/m^3.
- A simple rebound model was used for ice particle impacts. This model assumed a lossless impact with a Coefficient of Restitution of 1.0 and a Coefficient of Dynamic friction of 0.0.
- The rebound model assumed no breakup and 100% rebound and hence no surface deposition was generated.
- An implementation of the Glenn Ice Crystal Phase Change Model was used to determine the particle temperature, melting fraction, sublimation and evaporation during the particle trajectory integration.

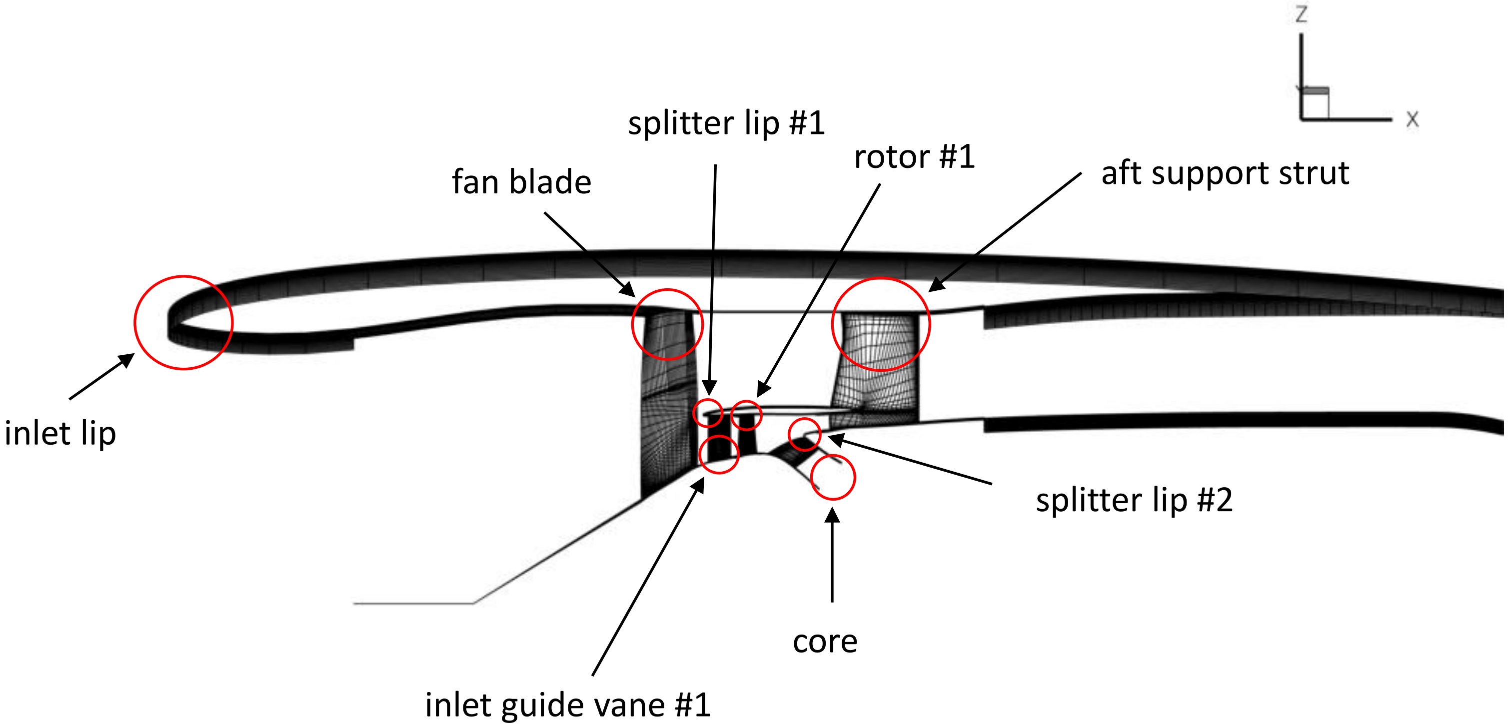
E^3 Engine Surface Model



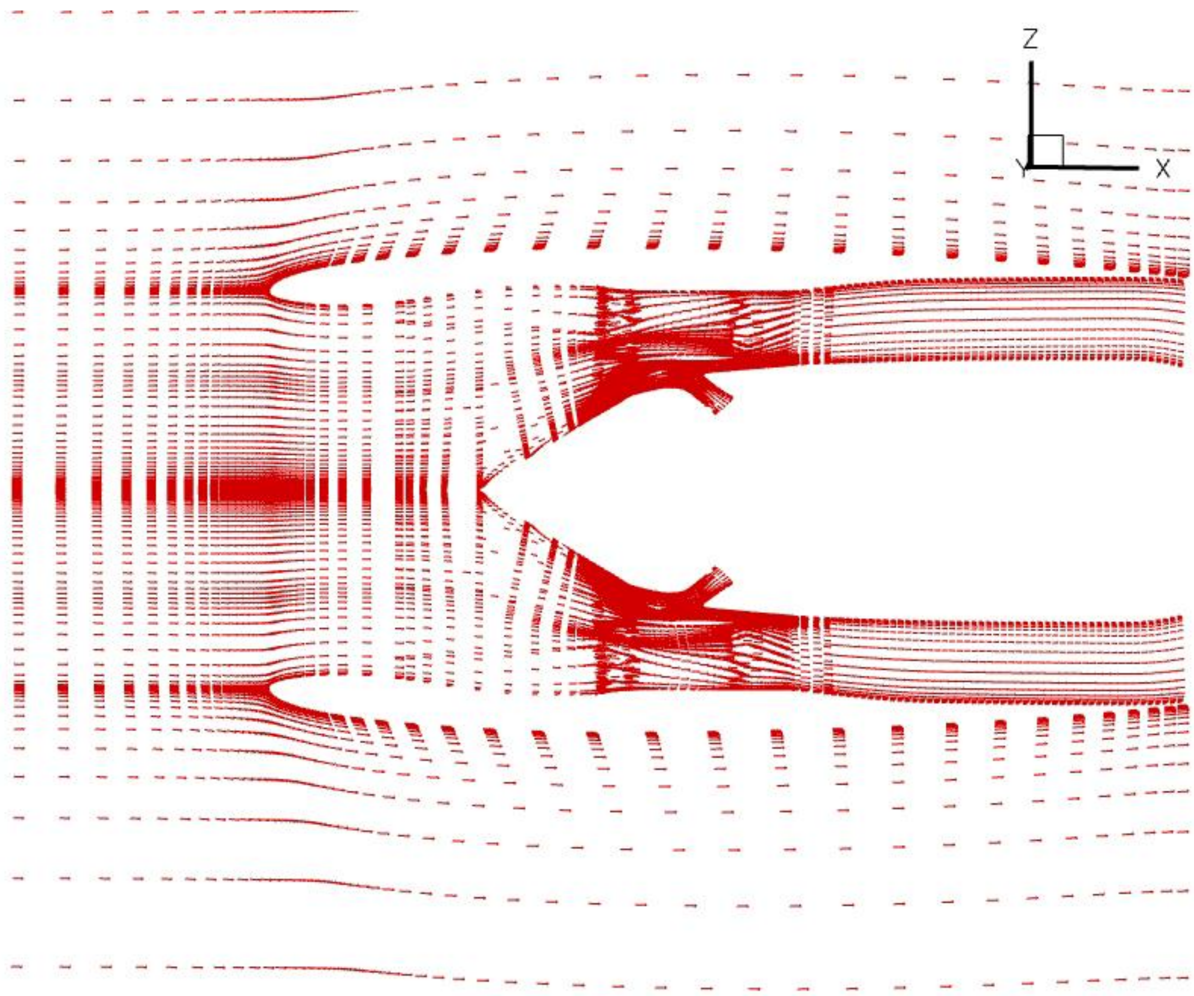
E^3 Engine Grid Block Structure



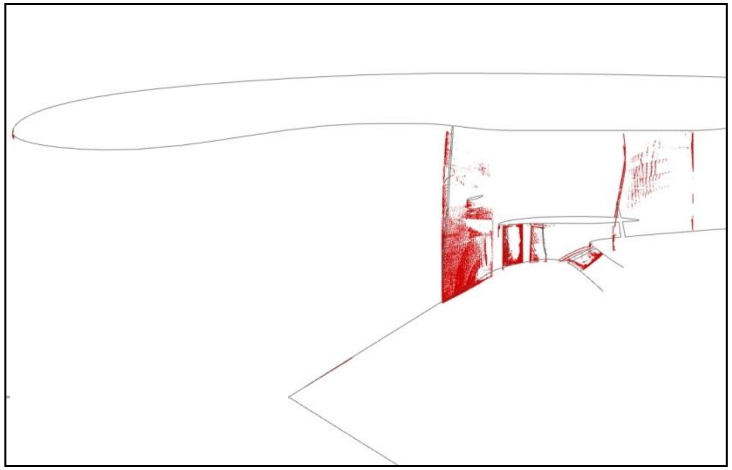
E^3 Engine Element Designations



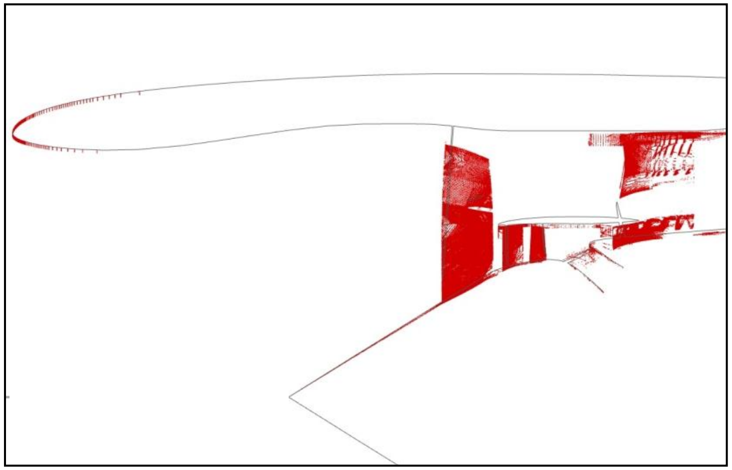
E^3 Engine ADPAC Flow Vectors Along Centerline



Axial Droplet Impact Locations for E^3 Engine

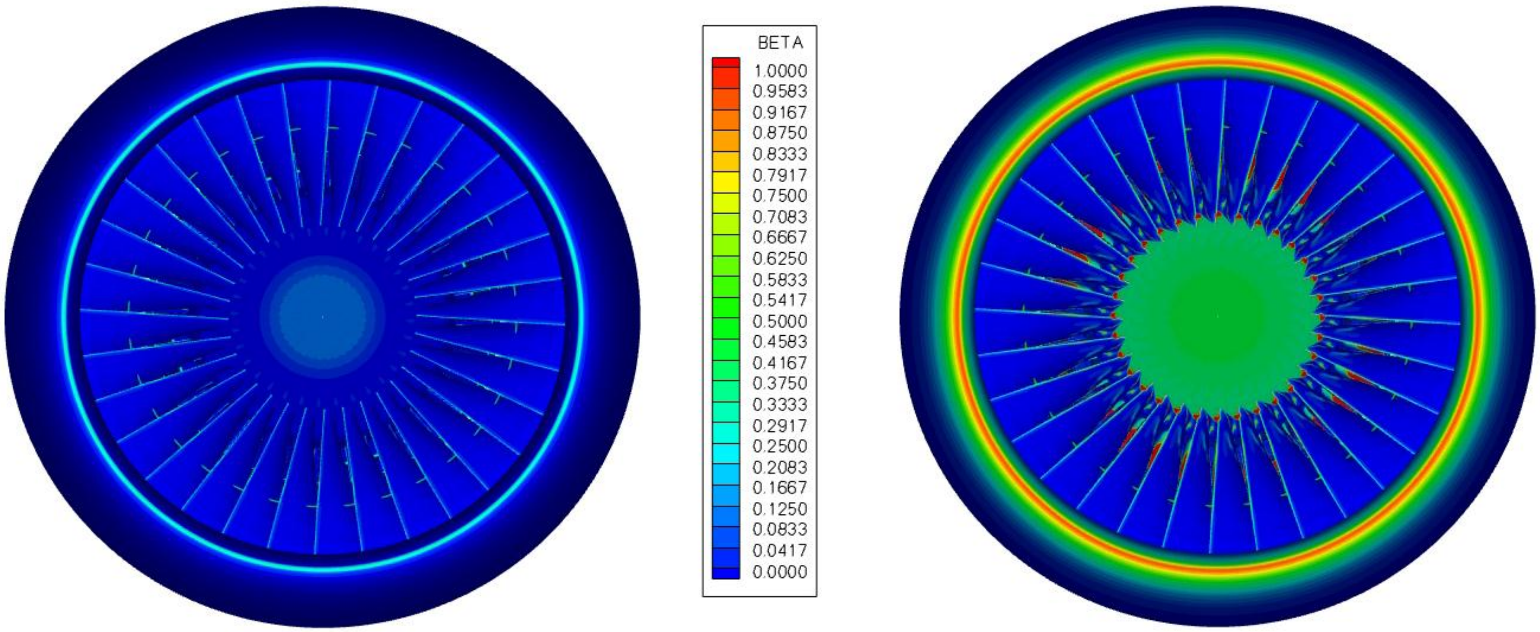


5 μm particle



100 μm particle

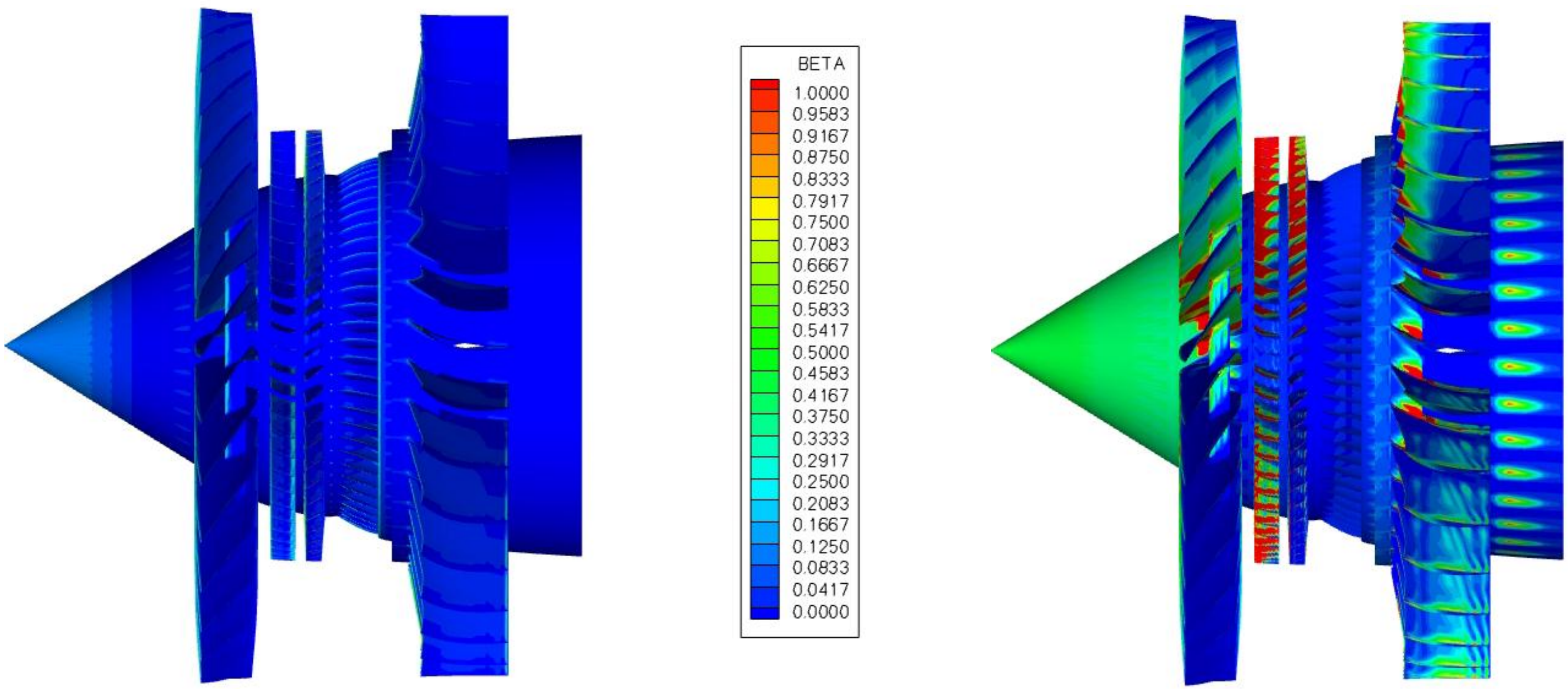
Impingement Efficiency Results for E^3 Engine



5 μm particle

100 μm particle

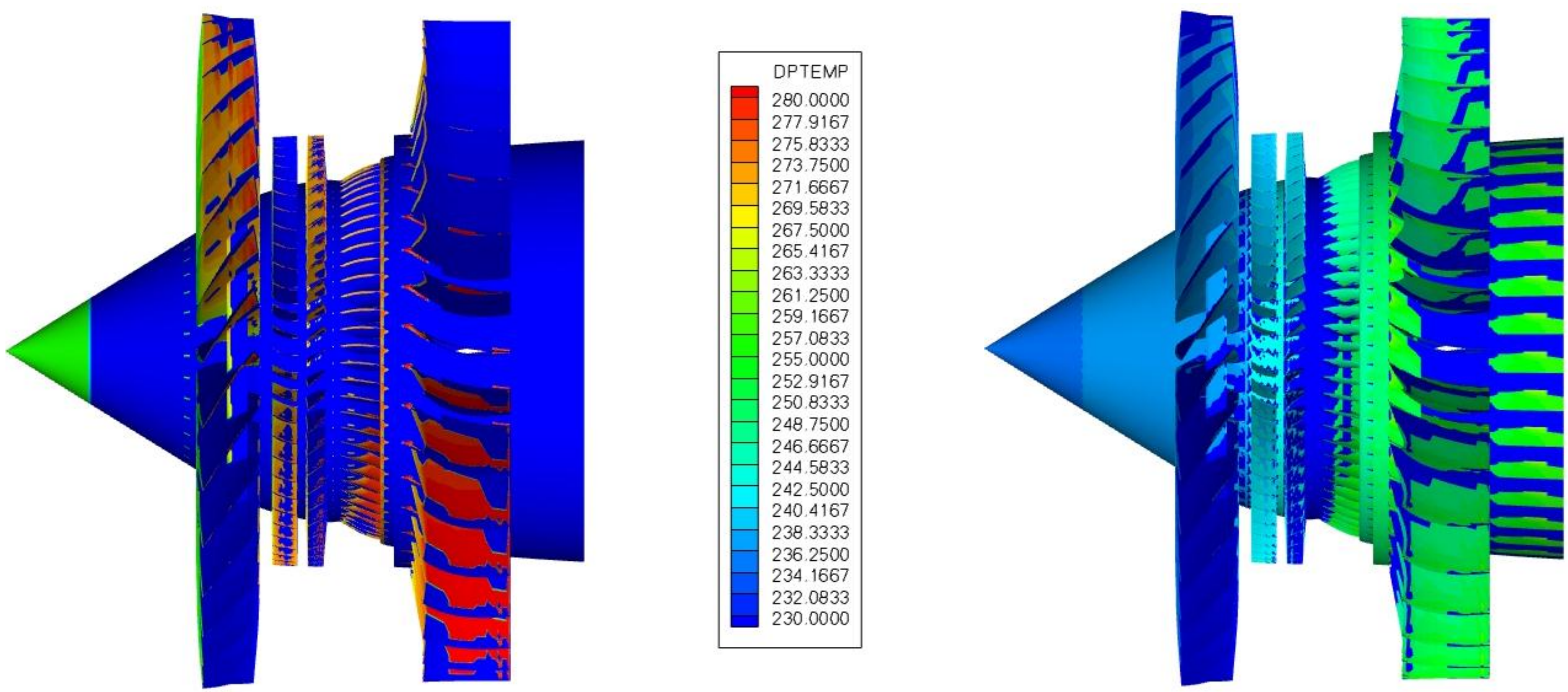
Impingement Efficiency Results for E^3 Engine



5 μm particle

100 μm particle

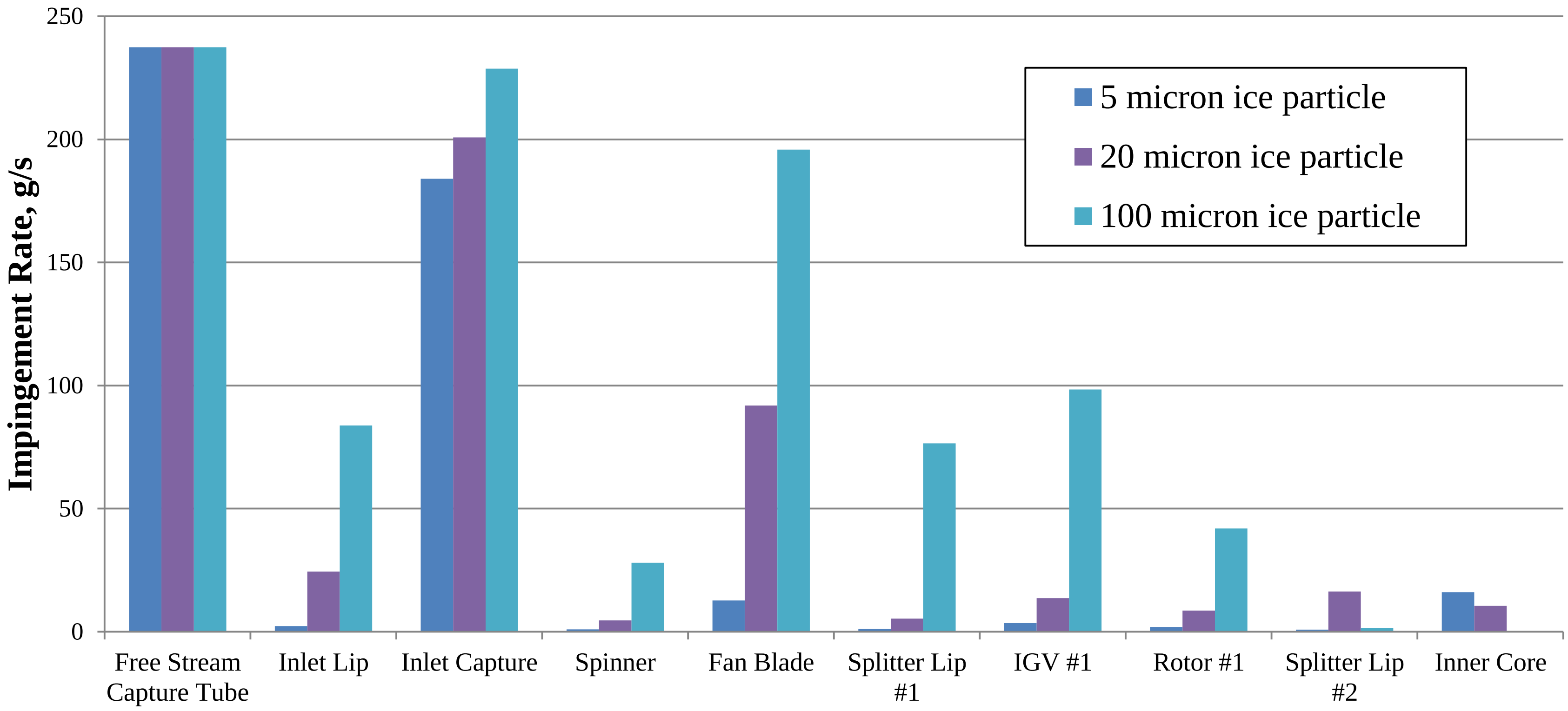
Particle Impact Temperature for E^3 Engine



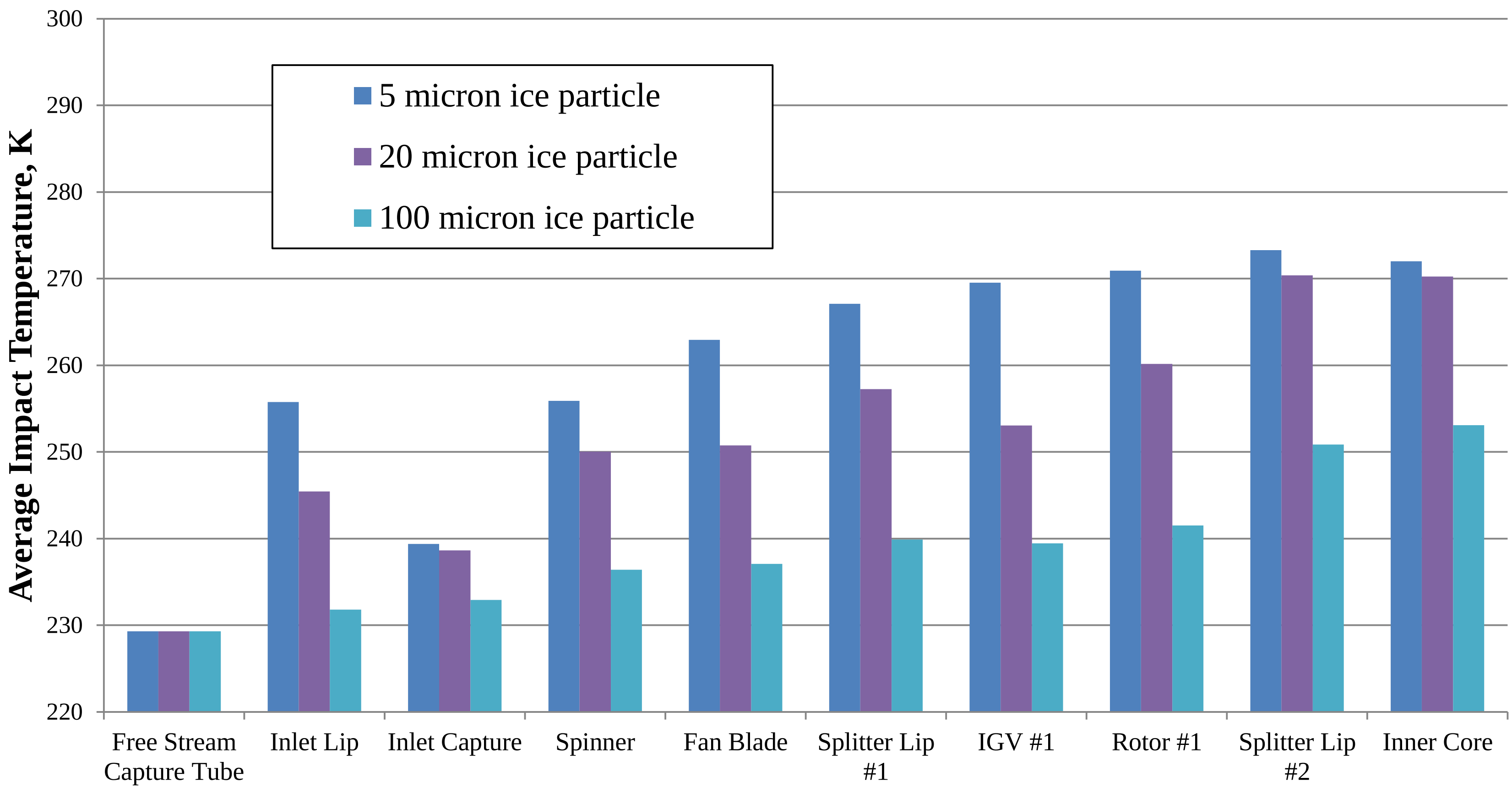
5 μm particle

100 μm particle

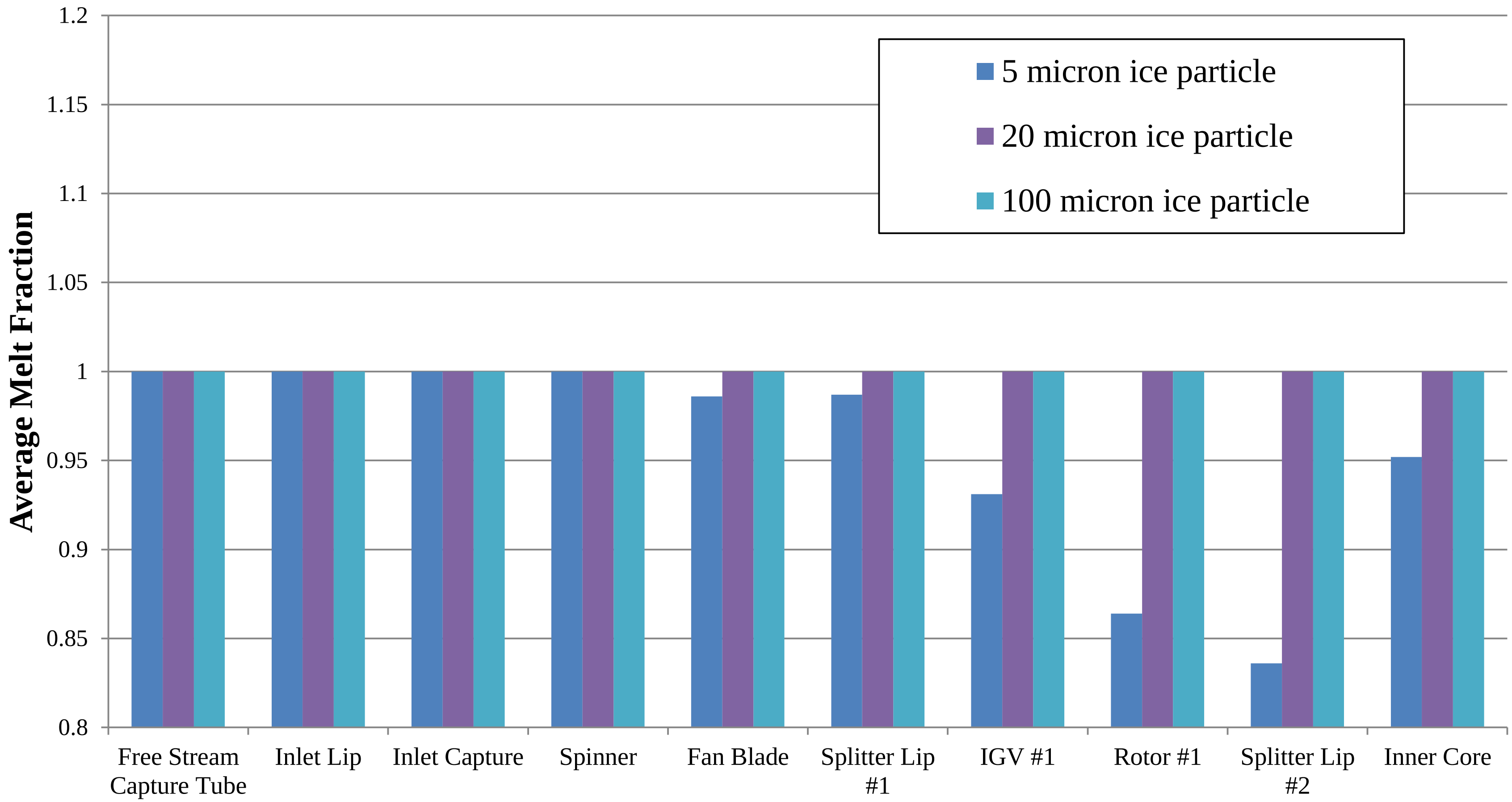
Impingement Rates for Various E^3 Components



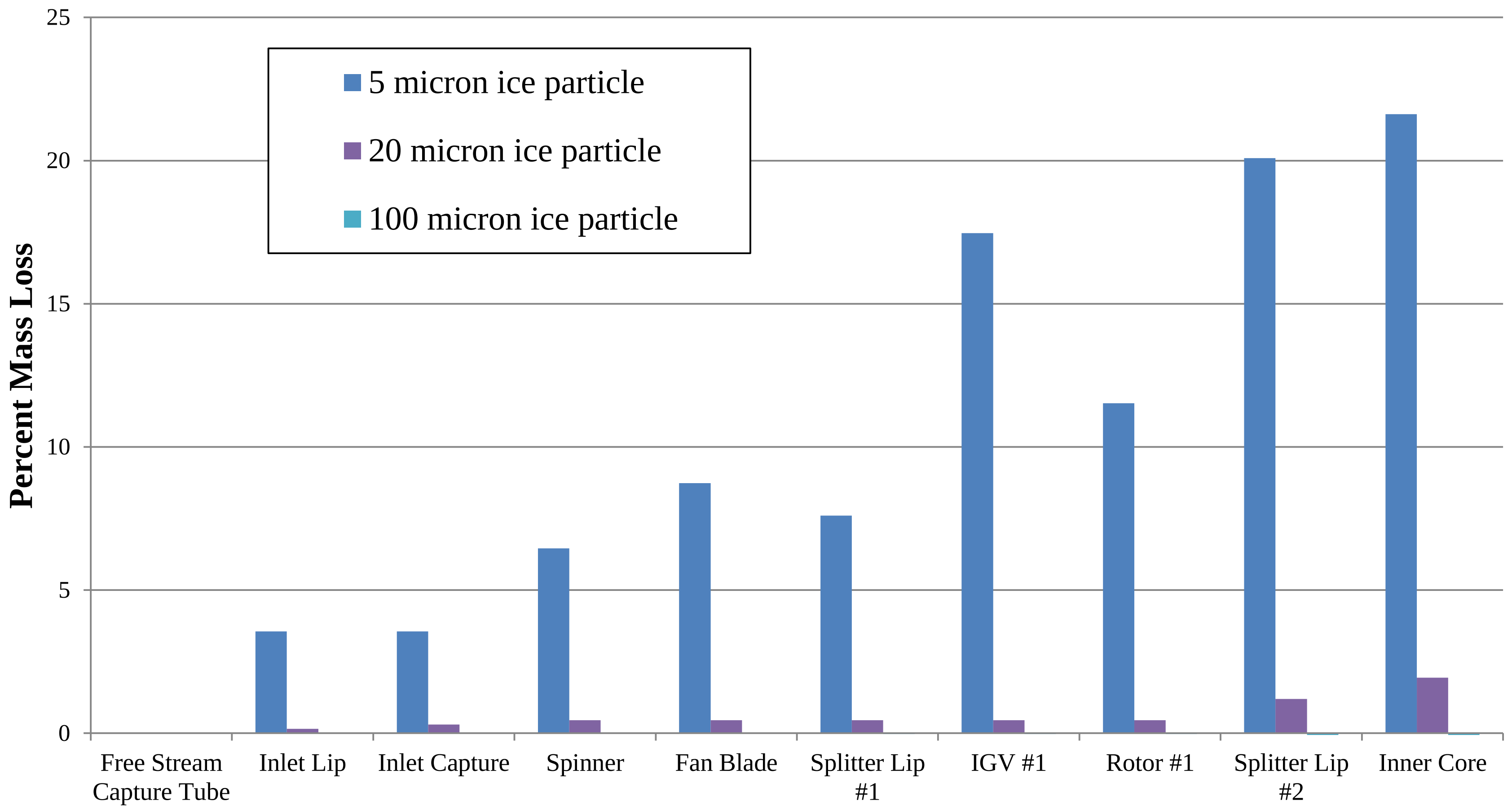
Average Particle Impact Temperature for Various E^3 Components



Average Melt Fraction for Various E^3 Components



Percent Mass Loss Due to Sublimation and Evaporation for Various E³ Components



Conclusions

- Predictions for ice particle impingement efficiency, temperature, and melting fraction were generated for the E^3 low pressure compressor using the Glenn Ice Particle Phase Change Model newly incorporated into LEWICE3D Version 3.2 and a flow solution from the ADPAC flow solver.
- The impingement efficiency results showed that as particle size increased average impingement efficiencies and scoop factors increased for the various components.
- The particle analysis also showed that the amount of mass entering the inner core decreased with increased particle size because the larger particles were less able to negotiate the turn into the inner core due to particle inertia.
- The particle phase change analysis results showed that the larger particles warmed less as they were transported through the low pressure compressor.
- Only the smallest 5 micron particles were warmed enough to produce melting and the amount of melting was relatively small with a maximum average melting fraction of 0.836.

Conclusions

- The results also showed an appreciable amount of particle sublimation and evaporation for the 5 micron particles entering the engine core (22%).
- These results suggest that the newly developed NASA Glenn “block-to-block” icing analysis method can be a useful tool for the analysis of turbomachinery subject to the HIWC environment.